Measuring the Top Quark Mass at CDF

Nick van Remortel

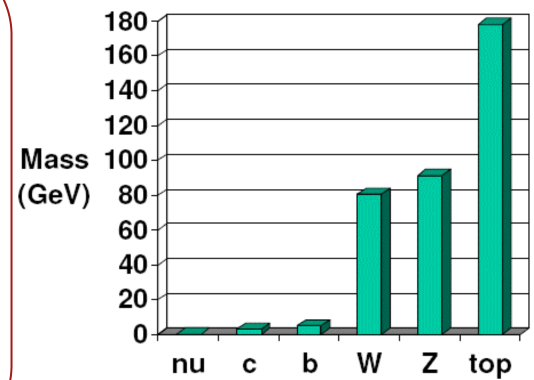
University of Antwerp, Belgium

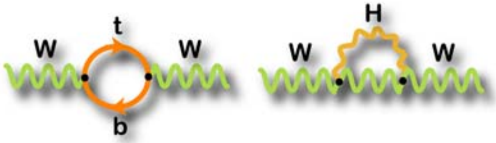
University of Helsinki, Finland

UNIVERSITY OF HELSINKI

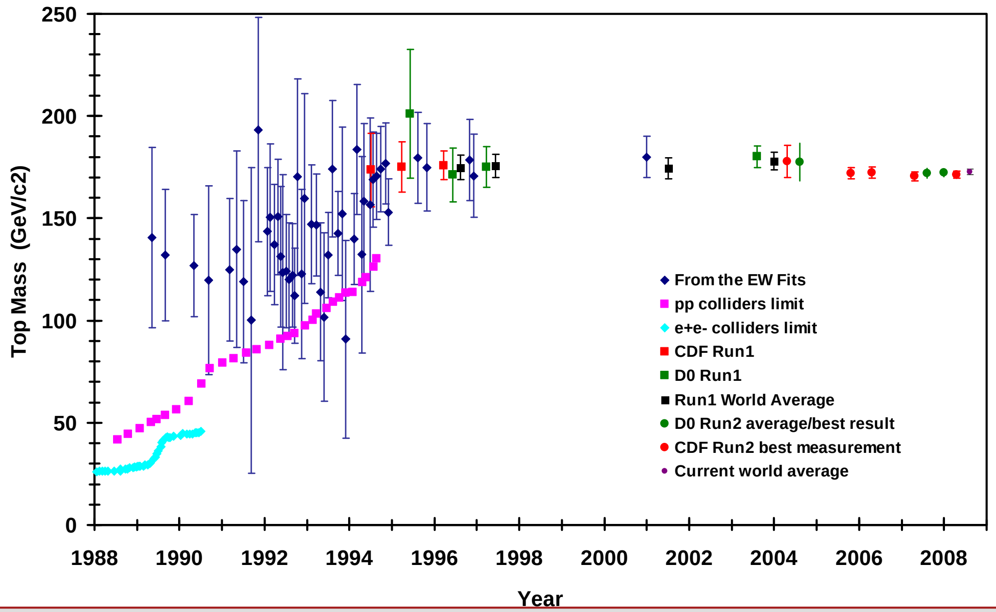
Top Quark Mass

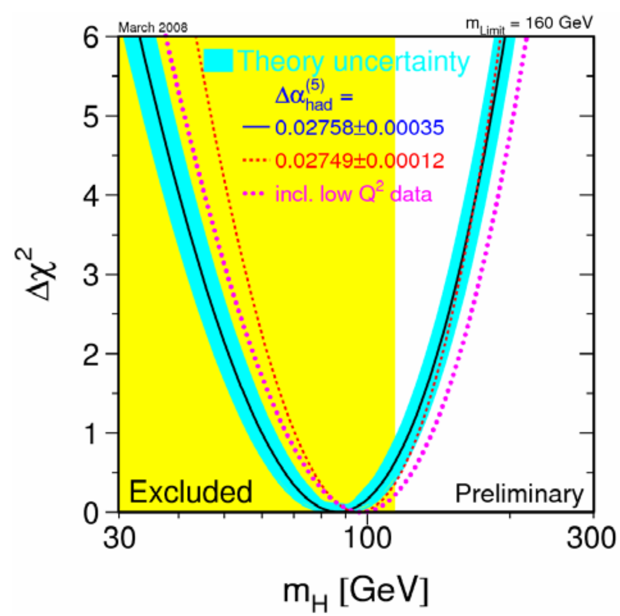
- *Fundamental parameter of the SM*
- *Heavy: Yukawa coupling ~ 1*
- *Together with the W mass constraining the SM Higgs*
  - *If Higgs is discovered: consistency check*
- *One of Tevatron's major successes*





m_H < 160 GeV @ 95 % CL

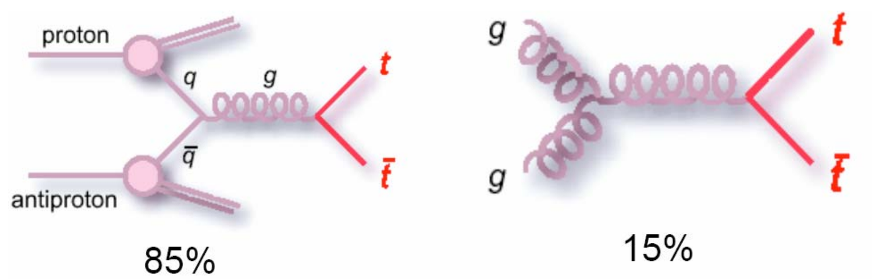




Top Quark Production & Decays

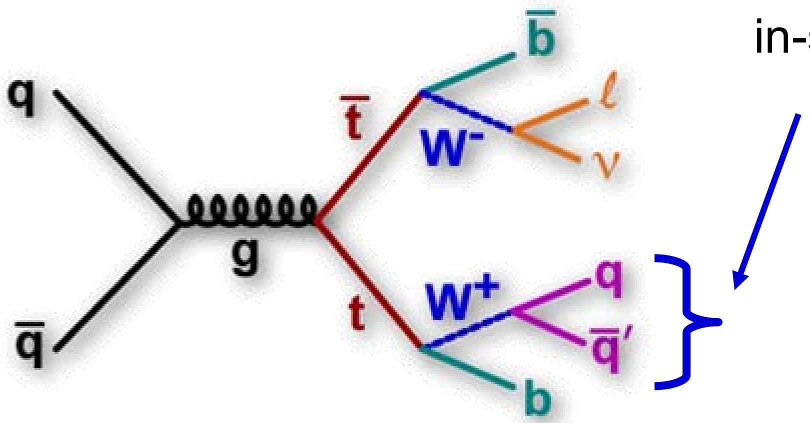
- **Di-lepton** channel: ~5%
  clean: both W decay to leptons, in practice uses only e, $\boldsymbol{\mu}$.
- **Lepton+Jets** channel: ~30%
  one W decays to leptons, the other decays to quarks
- **All-Hadronic** channel: ~45%
  both W decay to quarks, lowest S/B ratio

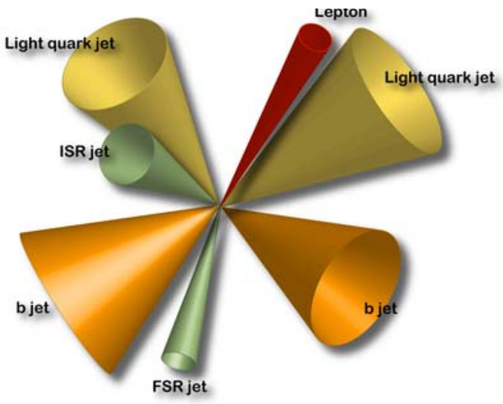
Mainly produced in pairs via strong interaction: $\sigma \approx 7$pb



Challenges: υ momentum, combinatorics, b-tagging efficiencies, jet energy scale.

Solutions: sophisticated analyses, in-situ W→jj calibration





Abstraction level

CDF analysis strategy

- ❖ Exploit all main 3 decay channels, including tau sensitive and all-hadronic
- ❖ Background estimates standardized in each channel
- ❖ Aim for one template and one matrix element measurement per channel
- ❖ Use baseline PYTHIA v6.2 MC to verify/correct for biases and pulls
- ❖ Blind analysis policy: only look at data after measuring 10 blind mass samples
- ❖ All latest measurements use 2fb^{-1} data

NEW IDEAS

- ✓ Use $W \rightarrow jj$ to perform simultaneous measurement of Jet Energy Scale
- ✓ Include cross-section information
- ✓ Combine several final states in one analysis
- ✓ Use observables that are less sensitive to dominant systematic uncertainties
  - lepton Pt spectrum
  - decay length of b-quark jets

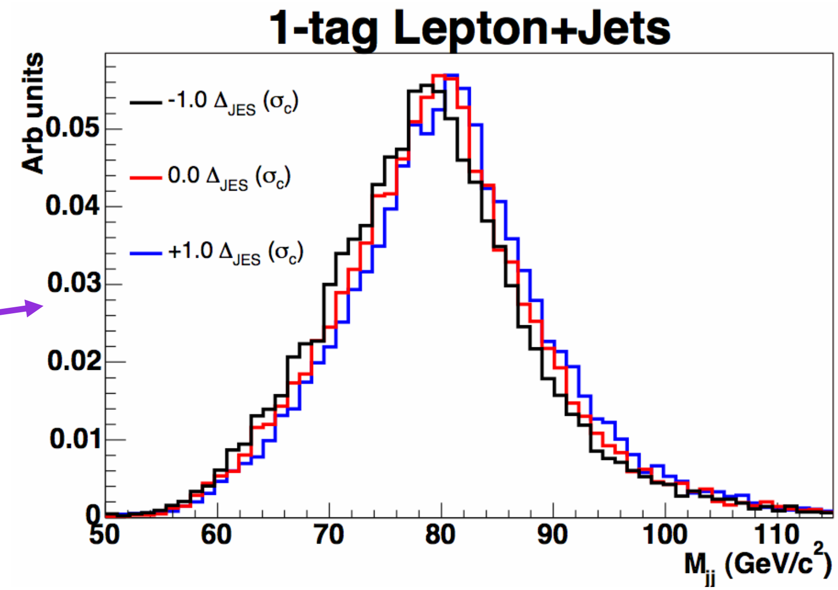
Large effort on gaining more confidence in existing and studies of new systematic error sources

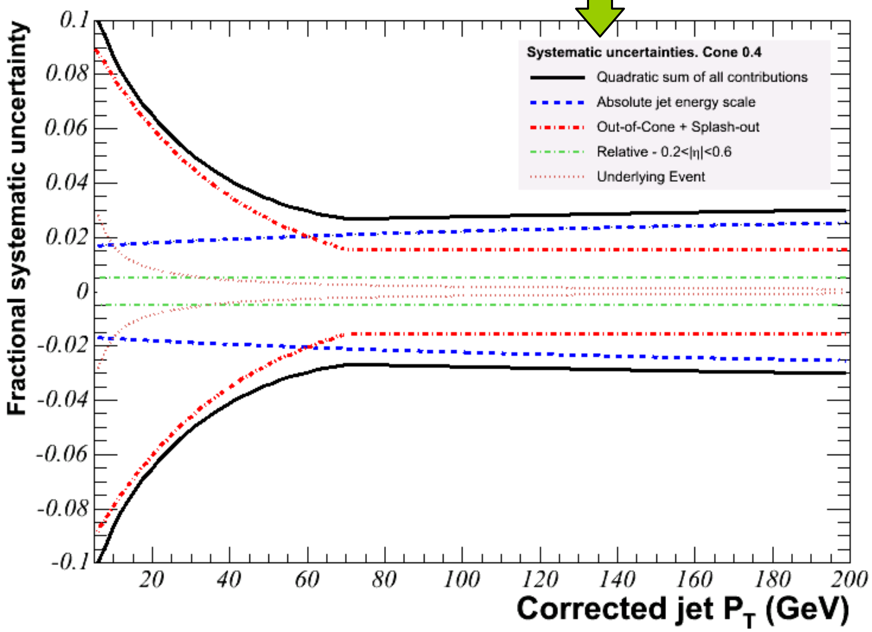
Constraining the JES with in-situ measurement

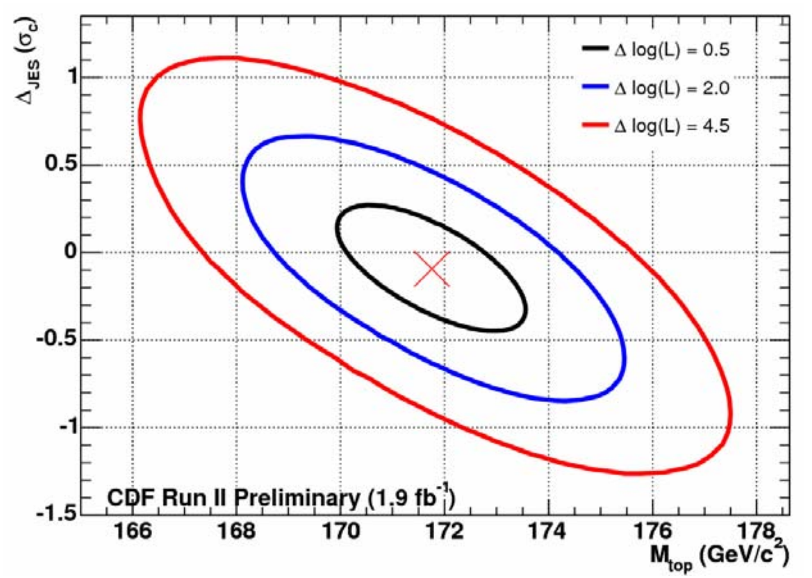
- JES used to be dominant source of systematic uncertainty in many analyses
- All mass analyses with at least one hadronic W in final state measure the JES simultaneously with M_{top}:

  Scale jet energies to match W mass spectrum by:

  $E_{jet}=E_{meas}(1+\Delta_{JES}*\sigma_{JES}(P_t))$







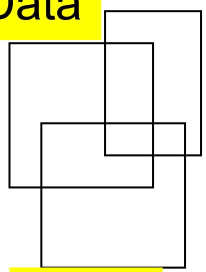
The Methods

Generic Template method

Data

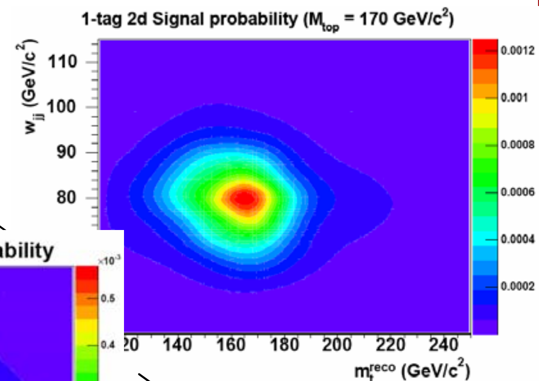
Bg MC

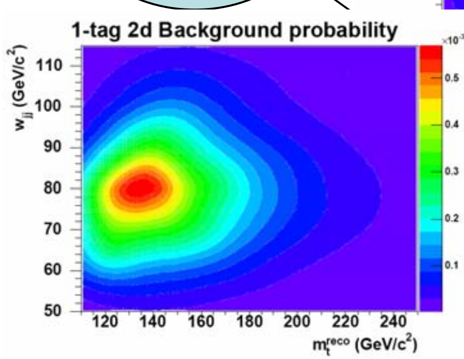
tt MC



Kinematic Fit

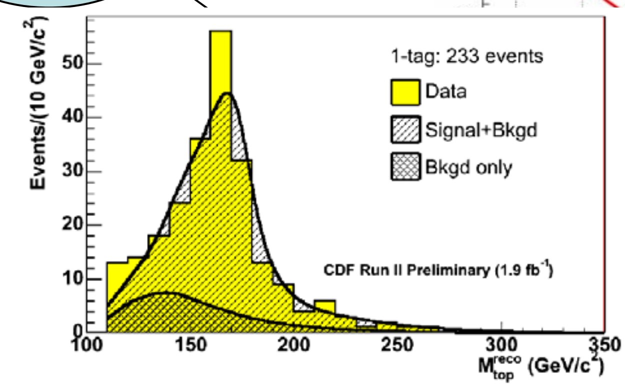
Sig & Bg Templates

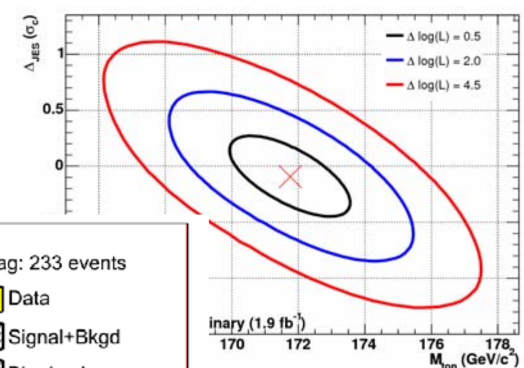




- Minimize χ^2 to reconstruct top mass for each combination
- Includes momentum/energy resolution
- For in-situ JES, use mass of hadronic W as 2nd variable
- Choose combination corresponding to smallest χ^2

Likelihood Fit





Result

- Choose one or more observables sensitive to true Mtop
- Generate MC based templates at different Mtop (and Δ_{JES}) values
- Determine most likely top mass by comparing real data with templates
- Robust, but rely heavily on MC description of data

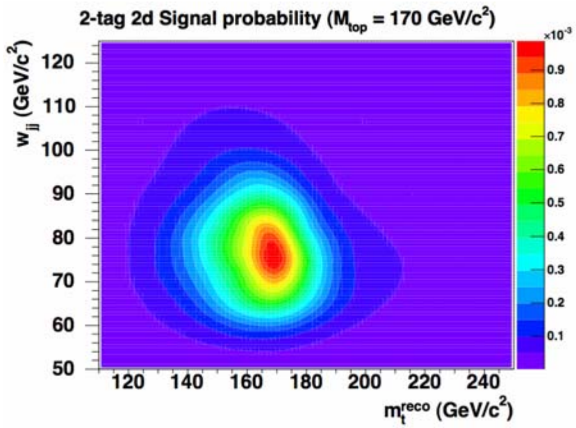
Combined dilepton - L+jets template

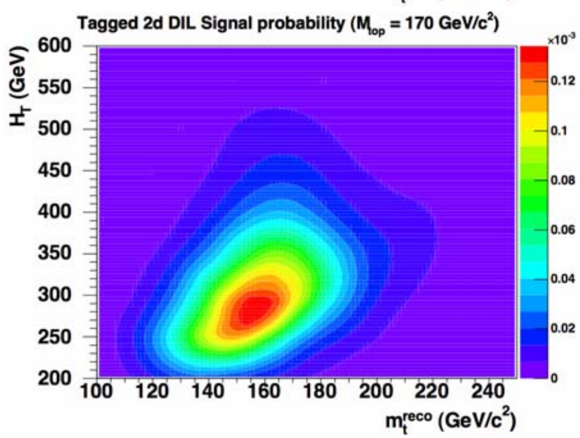
L+JETS

	1-tag	2-tag
$Wb\bar{b}$	9.1	2.1
$Wc\bar{c}$	5.0	0.4
Wc	3.3	0.1
W(mistags)	10.4	0.2
single top	2.0	0.7
diboson	2.4	0.2
QCD	10.4	0.3
Total Background	42.7±12.5	4.2±1.9
$t\bar{t}$ (6.7 pb)	156.7	76.6

DILEPTON

	0-tag	tagged
WW	6.3 ±1.0	0.2 ±0.04
WZ	1.5 ±0.2	0.03 ±0.00
ZZ	1.1 ±0.8	0.1 ±0.1
$DY\tau\tau$	4.3 ±1.3	0.2 ±0.1
$DYee,\mu\mu$	11.7 ±1.9	0.6 ±0.1
fakes	5.6 ±0.4	1.2 ±0.2
Total Background	30.4 ±4.1	2.4 ±0.4
$t\bar{t}$ (6.7 pb)	40.1 ±3.1	55.8 ±4.2





- Use dijet mass of hadronically decaying W as second observable, to constrain JES
- Apply the JES measurement to dilepton events
- Fit neutrino momenta and test compatibility with measured missing E_T as function of reconstructed top mass
- m_t^{reco} = mass at peak of probability weight distribution as first observable
- Second observable is the H_T (scalar sum MET, lepton PT, jet PT) in the event

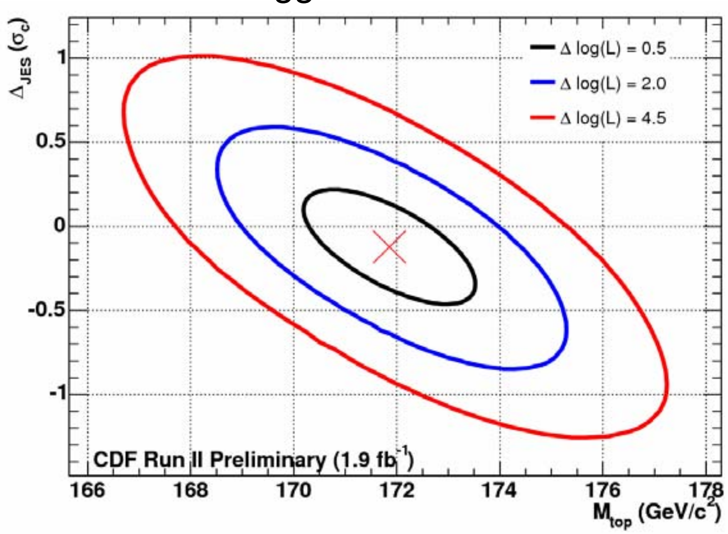
- Typical S/B for dilepton: 1:1 (0 tag); 20:1 (2 tags)
- Typical S/B for l+jets: 4:1 (1 tag); 20:1 (2 tags)
- Most background shapes/kinematics are MC-based, except for fakes/QCD
- Rates are typically a combination of data and MC
- B-tagging reduces background significantly

Result on combined dil – l+jets template

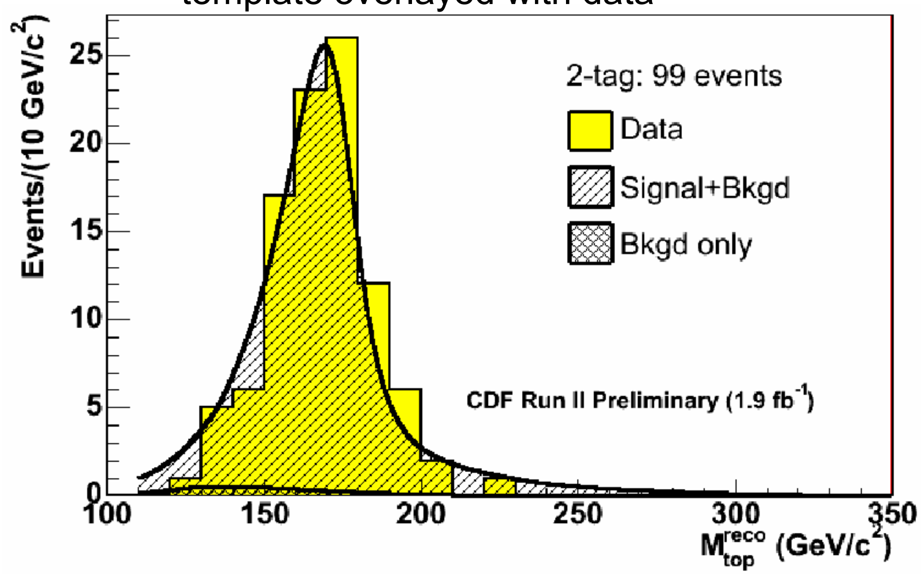
Advantages of combining 2 channels in one analysis:

- Combined fit using a floating JES (same JES for both channels)
- Not requiring the assumption of Gaussian measurements, use full likelihood curves instead
- Intrinsic treatment of correlations in systematics

Combined DIL- L+jets tagged and untagged likelihood



Example of 1D signal and background template overlayed with data

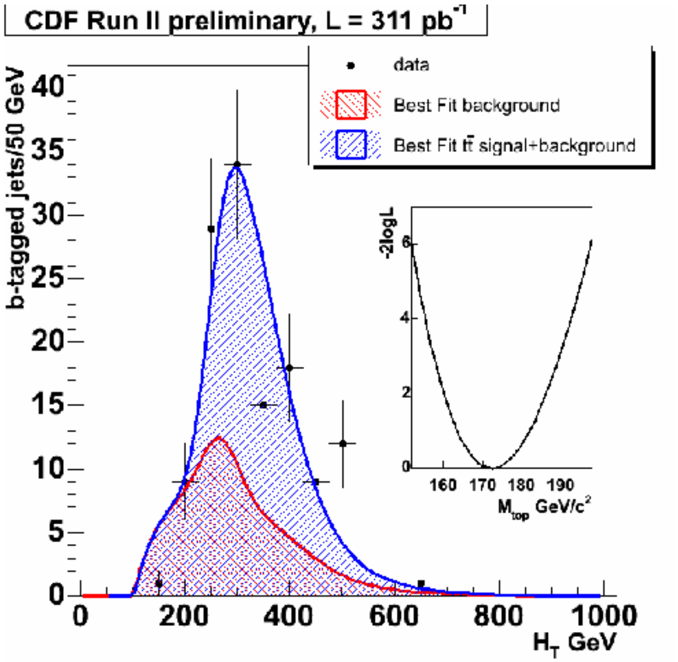


Mtop = 171.9 +/- 1.7 (stat.+JES) +/- 1.0 (syst) GeV/c^2 = 171.9 +/- 2.0 GeV/c^2

Orthogonal measurements

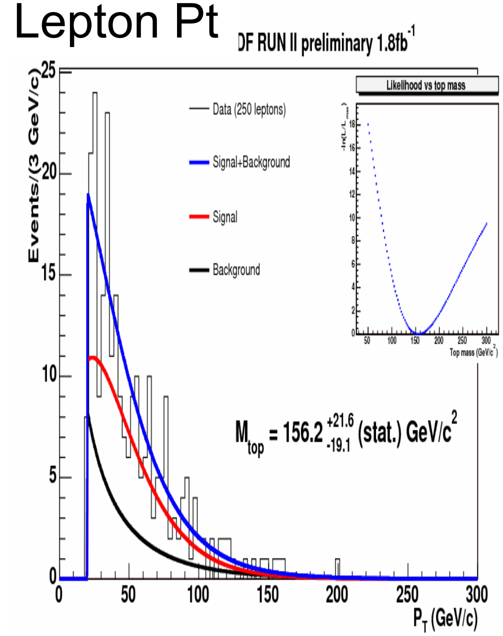
Template based methods that are strongly independent from mainstream analyses

Be sensitive to $W \rightarrow \tau\nu$
(missing E_T + jets)

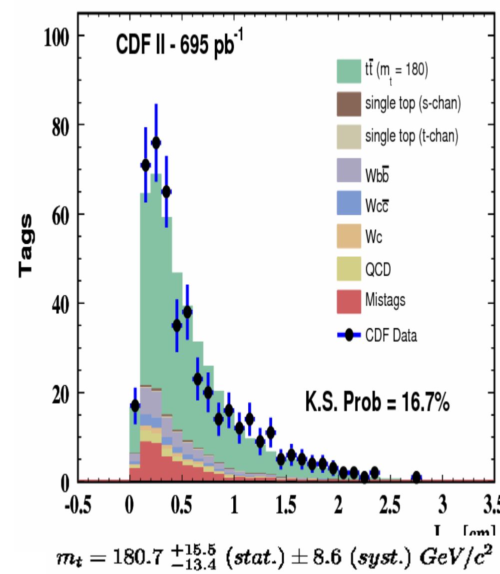


Rely on observables less sensitive to Jets

Lepton Pt



Decay length of b's



See N. Giokaris' talk

All of these have large statistical uncertainties, but could be useful at LHC

Generic Matrix Element Method

probability to observe a set of kinematic variables *x* for a given top mass

$d^n\sigma$ is the differential cross section
Contains (LO) **matrix element** squared

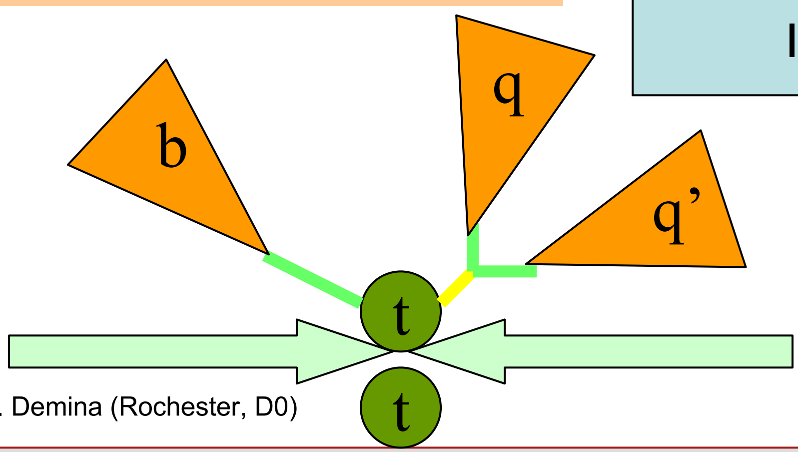
W(x,y) is the probability that a parton level set of variables *y* will be measured as a set of variables *x*

$$P_{\text{sgn}}(x;m_t) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y;m_t)\, dq_1\, dq_2\; f(q_1)\, f(q_2)\, W(x,y)$$

f(q) is the probability distribution than a parton will have a momentum *q*

Normalization depends on m_t
Includes acceptance effects

Integrate over unknown q_1,q_2, y



R. Demina (Rochester, D0)

- Maximal extraction of information, but phase space integration is very CPU intensive
- Needs to be calibrated with MC at different M_{top} values
- Additional background probability term with varying level of sophistication

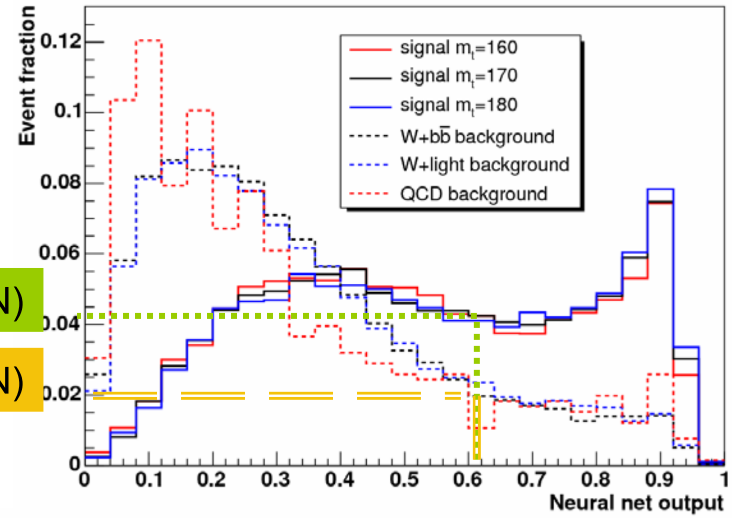
ME in L+jets

<u>Optimizations w.r.t. textbook approach:</u>

- In addition to sequential selection cuts and b-tagging, use an event-by-event background probability obtained from Neural net:
  $f_B(NN)=B(NN)/(S(NN)+B(NN))$

S(NN)

B(NN)

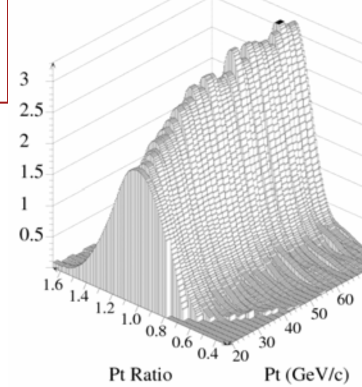


- Sum all likelihoods obtained from 24 possible Jet permutations to obtain single event likelihood:

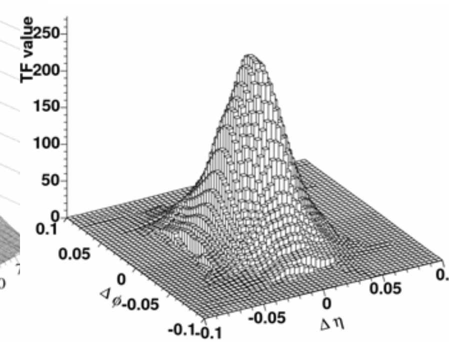
$$L(\vec{y}\,|\,m_t,\Delta_{\mathrm{JES}}) = \frac{1}{N(m_t)}\frac{1}{A(m_t,\Delta_{\mathrm{JES}})}\sum_{i=1}^{24}\boxed{w_i}L_i(\vec{y}\,|\,m_t,\Delta_{\mathrm{JES}})$$

Each combination is weighed with its compatibility with b-tagging information

Momentum TF



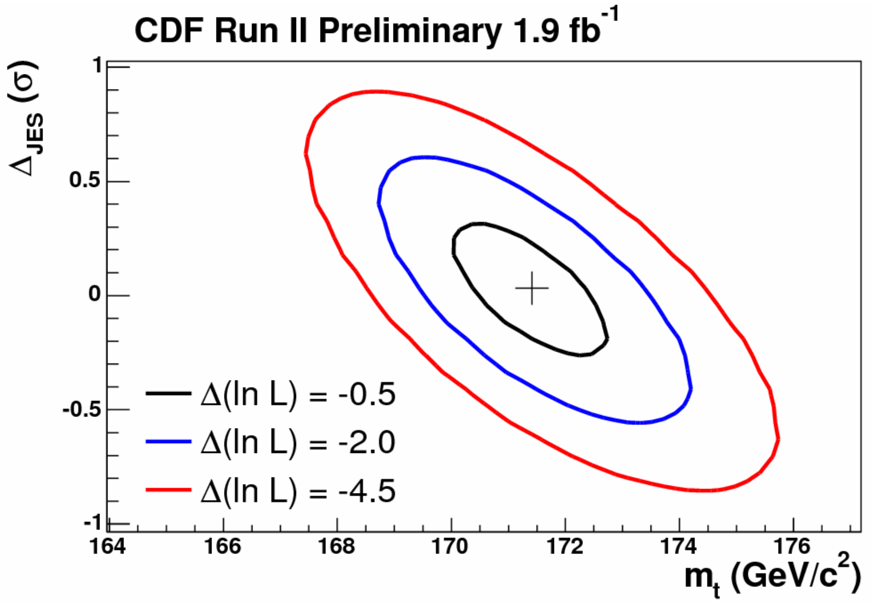
Angular TF

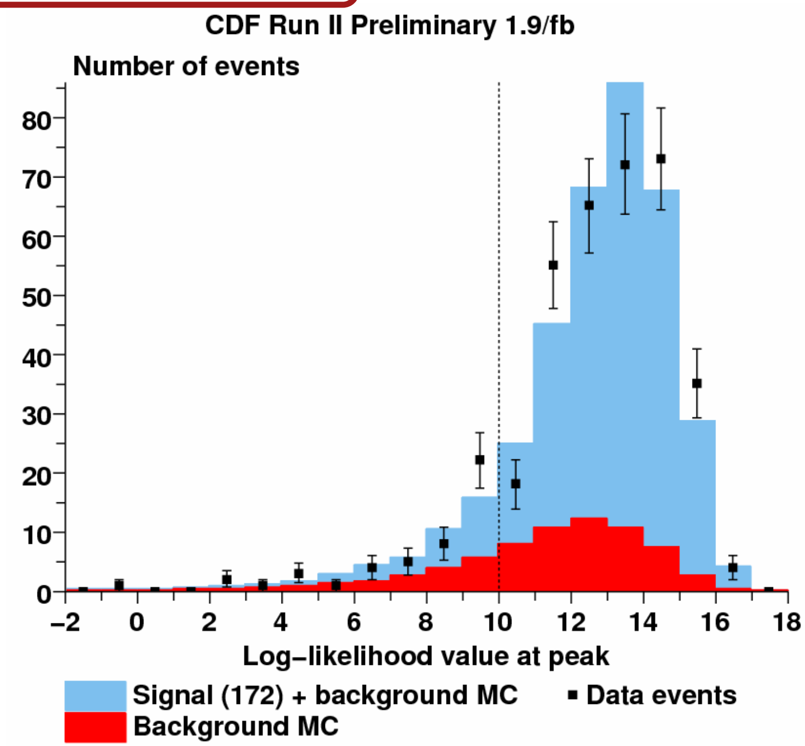


- Include angular transfer functions in addition to momentum transfer functions
- Leave the Δ_{JES} correction to the jet momenta floating
- Subtract background likelihood from data

ME in L+jets results

CDF's most precise measurement!





1% relative precision

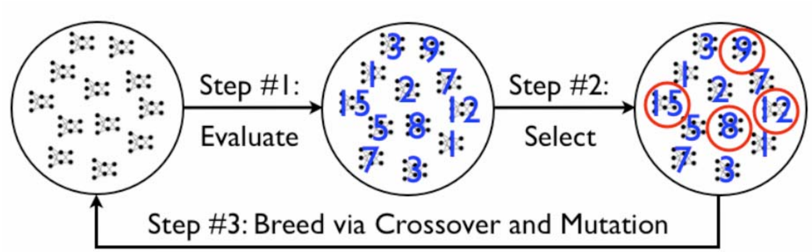
Mtop = 171.4 +/- 1.5 (stat.+JES) +/- 1.0 (syst) GeV/c^2 = 171.4 +/- 1.8 GeV/c^2

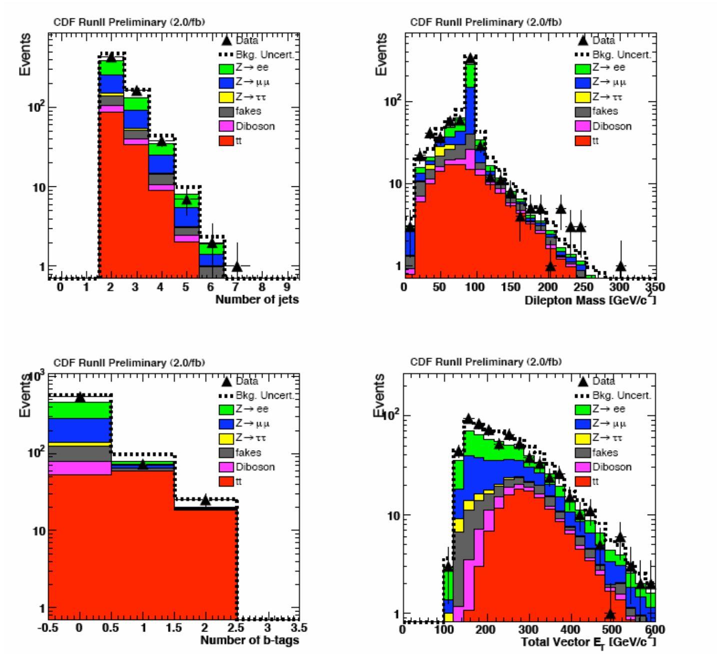
ME in dilepton

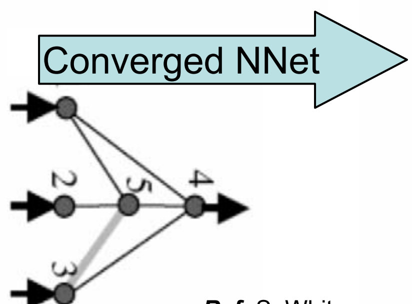
Event selection optimized to yield smallest expected statistical uncertainty by means of neuro-evolution:

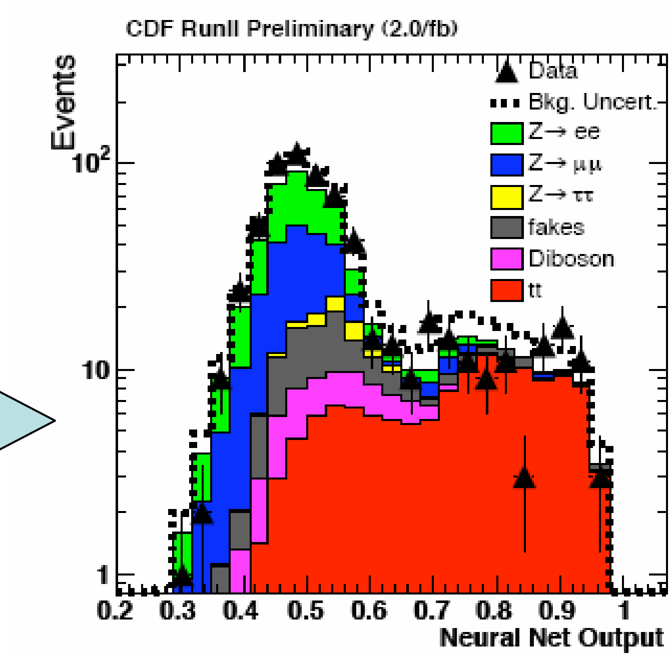
- Start with random collection of neural nets
- Determine analysis sensitivity of each network (fitness function)
- Discard low sensitive nets and combine topology and node weights through mutation

Neuro-evolution optimization







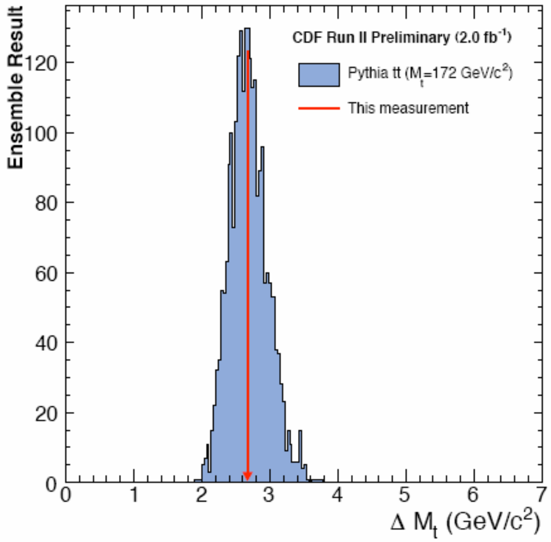


Ref: S. Whiteson and D. Whiteson, *Proceedings of the Nineteenth Annual Innovative Appllications of Artificial Intelligence Conference*, p1819-1825, July 2007
K. Stanley and R. Miikulainen, *Evolutionary Computation* 10(2):99-127, 2002

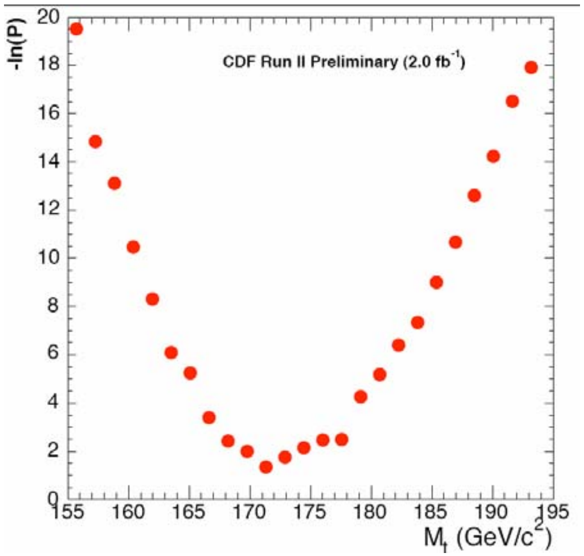
ME in Dilepton results

- Main background sources are subtracted separately using their own differential cross section (by MADGRAPH & MCFM) and weights dependent on number of b-tags in each event
- No handle on the JES which is by far the dominating systematic uncertainty

Mass uncertainty improved by 20%



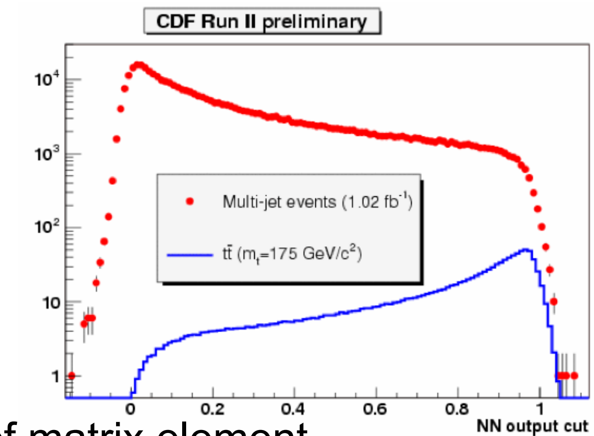
Final Mass likelihood from Data



Mtop = 171.2 +/- 2.7 (stat.) +/- 2.9 (syst) GeV/c^2 = 171.2 +/- 4.0 GeV/c^2

Ideogram analysis in all-had

- ❑ Neural network selection common with x-section measurement (see A. Castro's talk)
- ❑ Additionally demand >2 btags and exactly 6 jets in final state: S:B ~ 2:3



Event-by-event likelihood based on decay part of matrix element

$$L_S(M_t, \boxed{JES}) = \sum_{i=1}^{90} \boxed{w_i} \iint dm_t' \, dm_W' \, \boxed{G(m_t', m_W' | m_t^i, m_W^i, \sigma_t^i, \sigma_W^i, \rho_{t,W}^i)} \cdot \boxed{BW(m_t' | M_t, \Gamma_t) \cdot BW(m_W' | M_W, \Gamma_W)}$$

Compute compatibility of 6 final state jets with tt kinematics using χ^2 of kinematical mass fitter and b-tag information and distill weight, w_i , for each jet permutation

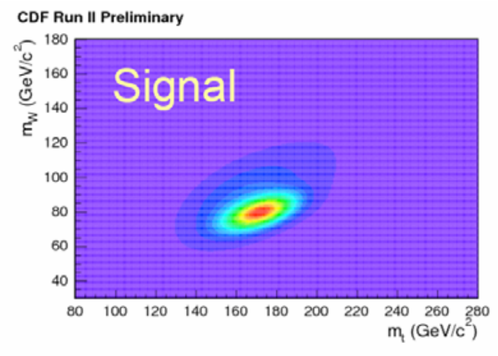
2D Gaussian resolution function for reconstructed top and W mass, including correlation term, $\rho_{t,W}$

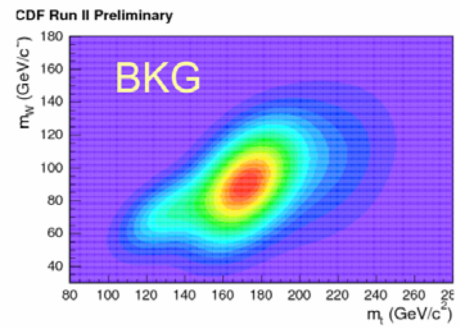
Both dependend on free floating JES

No observable decrease of performance was found by replacing Breit-Wigners with delta functions

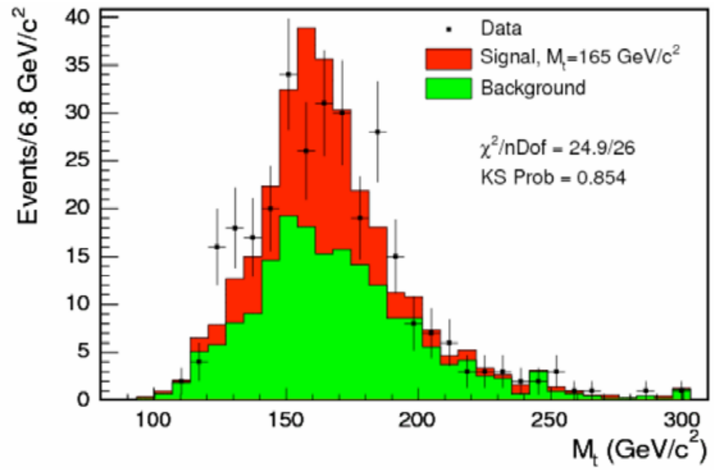
All-had ideogram analysis results

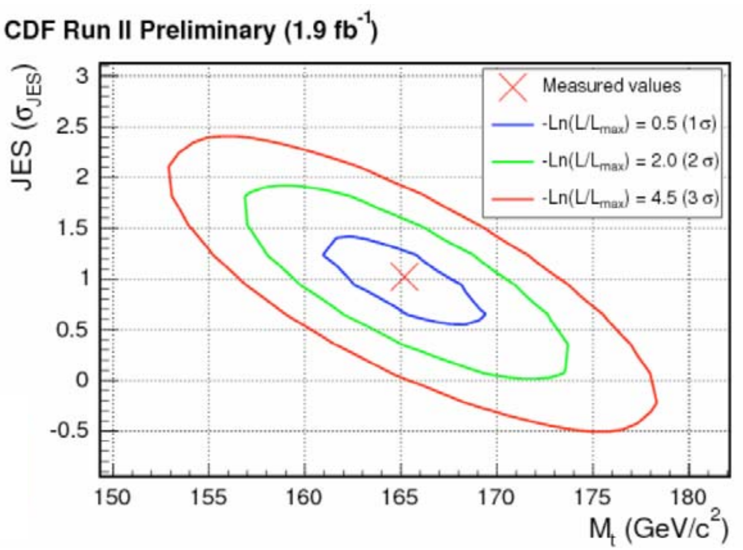
- Signal fraction measured from data and compatible with cross section measurements
- Backgrounds are described by 2D templates in reconstructed top and W mass





Mt value at maximum event likelihood





Mtop = 165.2 +/- 4.4 (stat.+JES) +/- 1.9 (syst) GeV/c^2
= 165.2 +/- 4.8 GeV/c^2

Systematic Uncertainties

- Mtop uncertainties have become dominated by systematics
- >1 yr CDF is revising all its systematic uncertainties for Mtop
- To have absolute confidence in the small numbers we quote
- To remove possible double counting in several sources
- To study carefully new physics effects that can be a new source
- Joint meetings with D0 to understand better each approach and possibly converge on common strategies

Our current list

1. JES (for non-in situ)
2. ISR&FSR
3. b-JES
4. Residual JES
5. PDF uncertainties
6. Generator & modeling
7. Multiple interactions
8. Background fraction & Shape
9. Lepton Energy scale

To be considered

- NLO Systematics: need to validate and compare NLO generators, possibly also include NLO PDF's
- Color reconnection: Model is intertwined with underlying event, need our experts to come up with reasonable tuning

...

Residual JES

Problem

- Use jets from hadronic W resonance in messy ttbar environment to measure the average response of jets in one number
- Typically choose to measure a global JES shift that is flat in pt and eta, or a shift according to the sum in quadrature of all JES systematics
- Our in-situ measured JES does not fully measure out shifts in JES scale along different parameter space curves (different shifts in jet pt and eta

Answer

- Evaluate every independent JES systematic separately when possible, and sum in quadrature
- Do this to re-compute acceptances and shapes for signal and background
- Compromises can be made for small background sources and JES correction levels for which the uncertainties are small

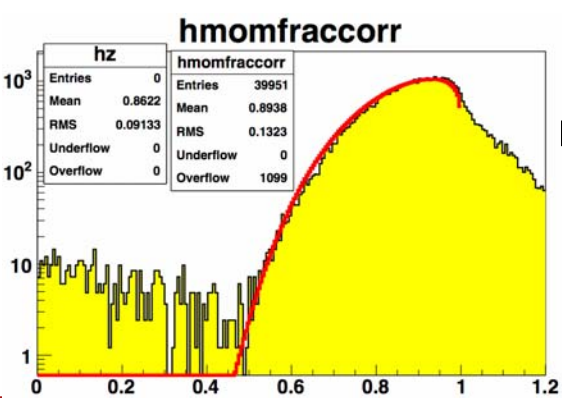
B-JES

Problem

- Derive JES from W daughter jets, but b jets carry most Mtop information
- 3 components of uncertainties due to difference between b and q jets:
    - B decay BR uncertainties (semi-leptonics!)
    - B fragmentation uncertainties
    - Calorimeter response uncertainties
- Currently vary b-jes with additional 1% variation to bracket these uncertainties

Using semileptonic branching uncertainties from PDG: 0.14 GeV < ΔMtop < 0.35 GeV

B fragmentation: vary Bowler paremeters (between LEP, SLD and our default) and calculate event weights , but we do not have access to <u>longitudinal momentum fraction of B-hadron wrt b quark: </u>ΔMtop < 0.20 GeV



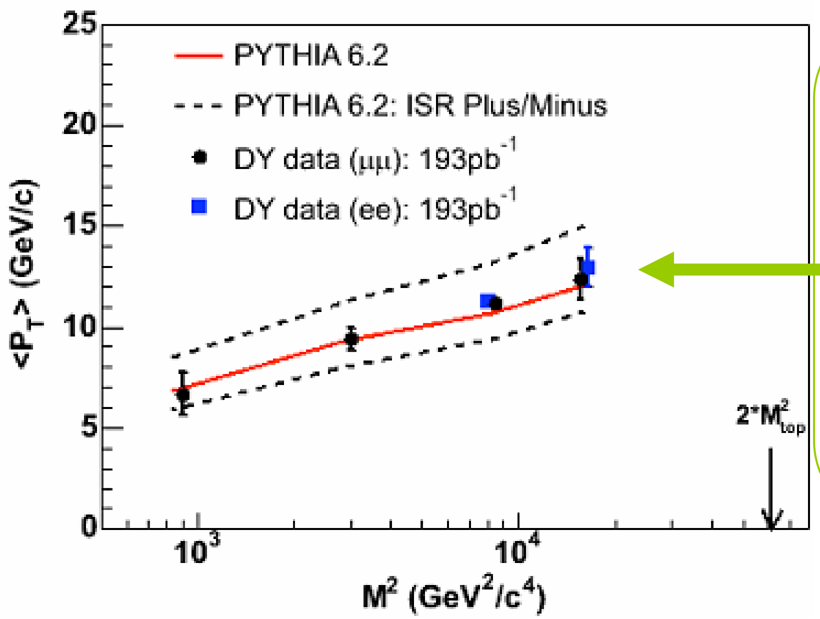
Will try fully simulated events with different Bowler parameters

Also: small effects found in M_{top} due to difference in absolute calorimeter response

ISR & FSR

Problem

- Use dedicated Pythia samples with increased/decreased amount of ISR/FSR
- Variations in pythia parameters are determined by studying dimuon events only sensitive to ISR
- FSR parameters are varied within similar bounds, assuming the physics is similar
- Extrapolation from DY data to ttbar events is large
- Pythia parameters control mainly the soft part of FSR, might overlook hard (NLO type) radiation



Will try to pin down this uncertainty band by using new data and adding higher mass points

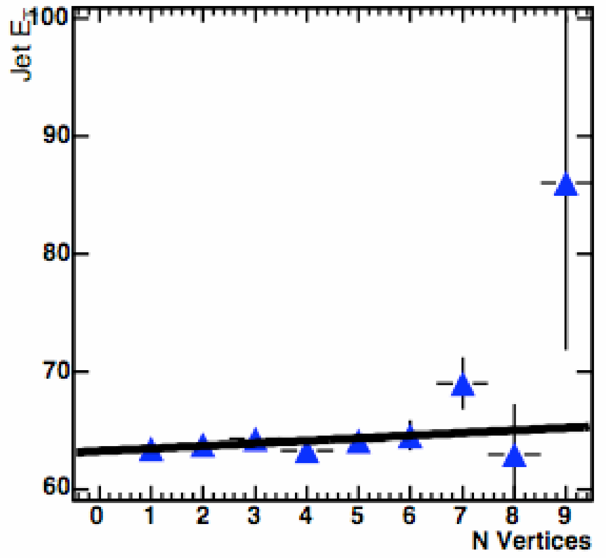
Currently changed to samples where ISR and FSR are simultaneously increased or decreased

Multiple interactions

Problem

- Our MC simulates only one parton-parton interaction per event
- We add additional min bias events according to our lumi profile and determine JES correction
- In ttbar events our MC still underestimates the amount of multiple parton-parton interactions in each collision
- How does this propagate into an Mtop uncertainty ?

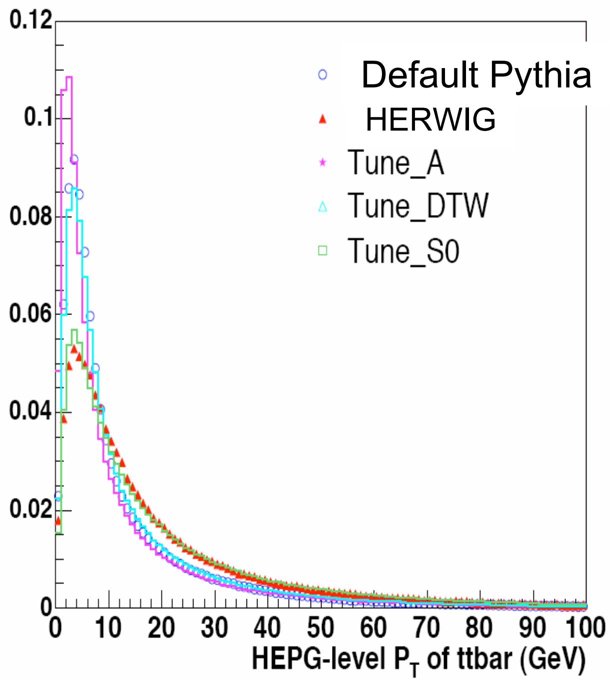
B-Jet Et increases with ~200 MeV
For each additional vertex



- We find mean of ~2 vertices per event in our current 2 fb^{-1} dataset
- We know that B-Jets affect M_{top} most
- We know how a 1% bjet ET increase affects M_{top}
- Total effect is O(200 MeV) on M_{top}

Remaining issues

- Generator systematics are treated in separate talks by U. Huseman and A. Hare
- Color Reconnection:
  - Up to recently, no good Tune available in CDF
  - We know Pt (ttbar) is most affected
  - We found that Pt (ttbar) in data corresponds well with that from HERWIG
  - CDF obtained Pt (ttbar) spectrum at parton level from CR authors and reweigted events

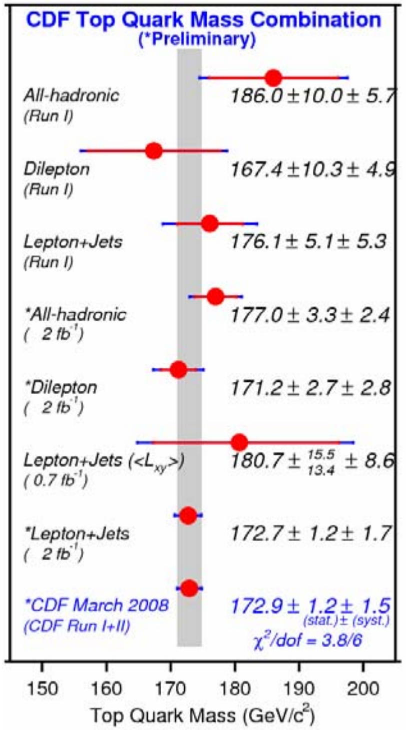


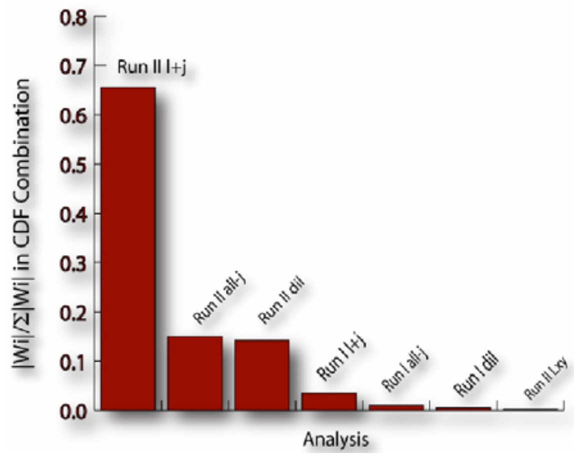
Obtained shifts after reweighting for S0 model were
Incompatible with our observed shifts wrt HERWIG:
ΔM_{top}= 0.5 GeV

Our current bracket around the CR uncertainty is
ΔMtop < 1.3 GeV
But likely to be much smaller

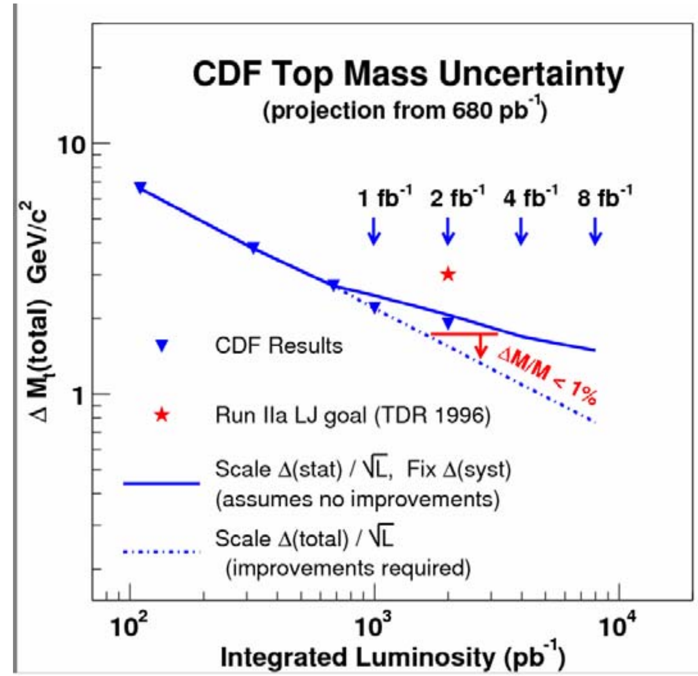
No one knows how much we are double counting with modeling/fragmentation effects

Combined results





See D. Glenzinski's talk



CDF average Mtop = 172.9 ± 1.2(stat) ± 1.5(syst) GeV/c^2

World average Mtop = 172.6 ± 0.8(stat) ± 1.1(syst) GeV/c^2

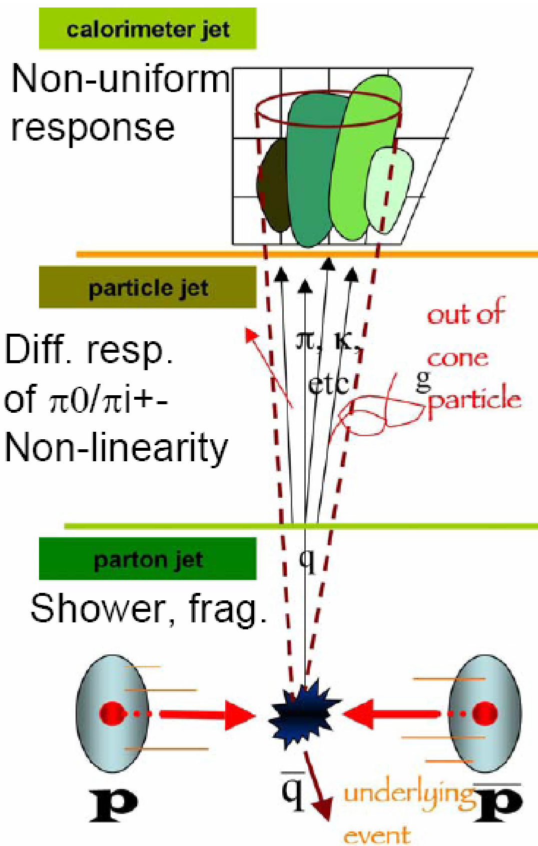
Conclusion

- Very large collective effort spent on top mass
- Top mass is now known to < 1%
- More data will be analyzed!
- Our accuracy will be hard to beat by LHC
- Need to be absolutely confident in the systematic uncertainties we quote
- One of the important legacies of the Tevatron

Thanks to all members of CDF Top team in making it happen

Backups

Jet Energy Scale (JES)



Correct to central region using di-jet events

Correct using MC tuned to E/p of test beam data

Correct for leakage radiation outside the jet clustering cone

Underlying event and multiple interactions

- JETS defined at calorimeter level using iterative cone with R=0.4
- Series of correction levels to obtain a parton Pt estimate
- Most corrections are data-driven and obtained from independent di-jet and γ+jet samples
- Same corrections apply to data and MC (signal & bg)
- Most top mass analysis do not correct for out-of-cone effects or underlying event activity
- All analyses assign systematic uncertainty due to all correction levels

Typical systematics tables

ME in L+jets

Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.1
MC generator	0.4
ISR and FSR	0.5
Residual JES	0.5
b-JES	0.4
Lepton P_T	0.2
Multiple interactions	0.1
PDFs	0.2
Background	0.3
Total	1.0

ME in dilepton

Source	Size (GeV/c^2)
Jet Energy Scale	2.5
Lepton Energy Scale	0.1
Generator	0.7
Method	0.4
Sample composition uncertainty	0.3
Background statistics	0.5
Background modeling	0.2
FSR modeling	0.3
ISR modeling	0.3
PDFs	0.6
Total	2.9

Ideogram in all had

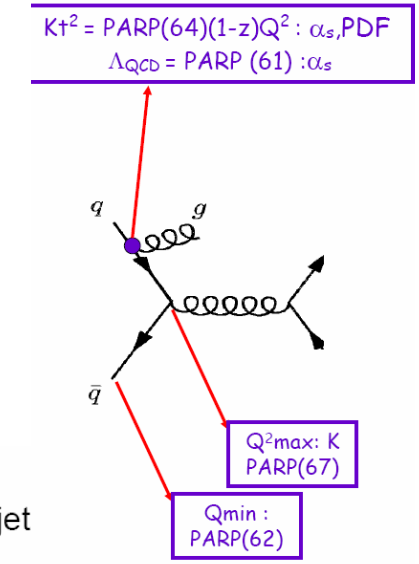
Source	ΔM_t (GeV/c^2)
ISR/FSR	1.2
MC Generator	0.8
Residual JES	0.7
Inst. lumi.	0.7
Bg Fraction	0.5
Bg Shape	0.4
PDF	0.4
B-JES	0.3
Calibration	0.2
Bg Statistics	0.07
Total	1.9

ISR-FSR systematics

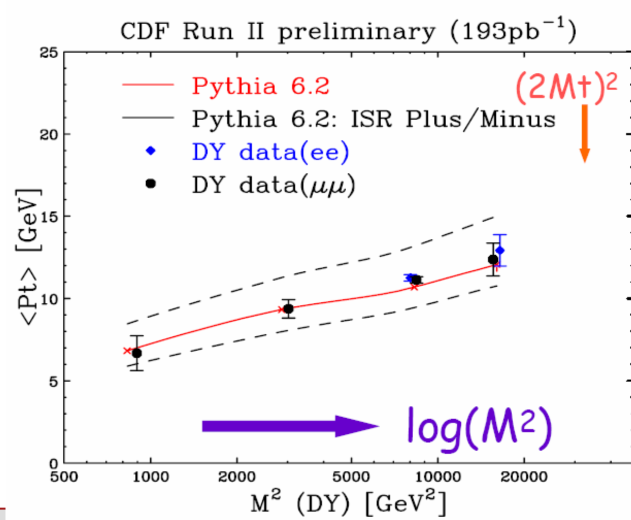
- FSR syst. is based on the ISR syst. studies
  - Both ISR and FSR have same parton shower process (DGLAP), except that the PDF evolution is only involved in ISR showering.

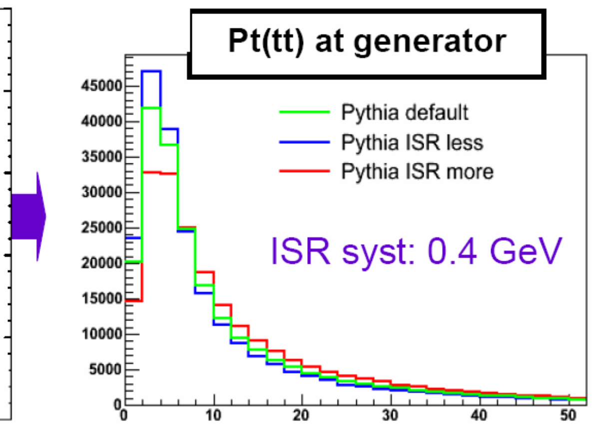
Pythia	FSR plus (Top std)	FSR minus (Top std)
PARP(72)	0.292 (5fl: LO)	0.073
PARP(71) D=4	8	2.0

Pythia	FSR plus (Top cntrl)	FSR minus (Top cntrl)
PARP(72)	0.292	0.073
PARJ(81) D=0.290	0.580 (4fl: LO)	0.145
PARP(71)	8	2.0



- Conservative ISR syst. (plus/minus) for ttbar are established
  - <Pt(dilepton)>: sensitive to only total size of ISR, but missing Njet
  - Extrapolate to top pair production region using LO MC

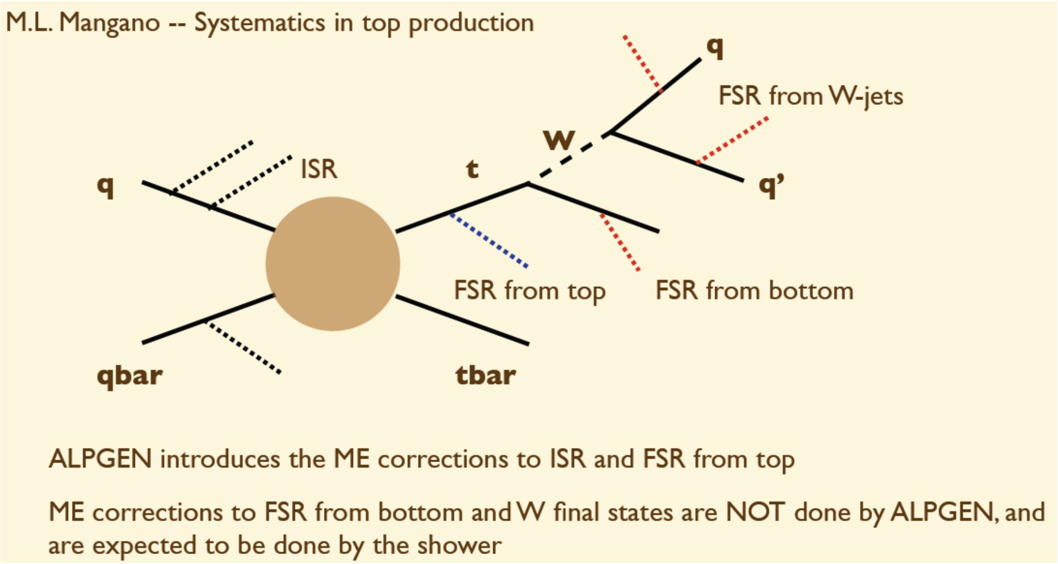




R-ratio in ISR/FSR

- Define

  R=N(ttbar + 0 jets) / N(ttbar + 1 or more jets)
- Measure R in ttbar l+jets data and compare it to MC (Alpgen).



D0 approach:

- Divide tt+0lp(excl), tt+1lp(excl), tt+2lp(incl) into l+3particle jets, l+4particle jets, and l+5 or more particle jets
- Vary the fraction of l+5 particle jets to get the right R

R(3pj +4pj) =1.33

R(5pj) =1.56

In data between 1.46 and 1.96

B-JES systematics

Old estimates

- Heavy quark fragmentation: $0.4\ \mathrm{GeV}/c^2$
- Semileptonic decays: $0.4\ \mathrm{GeV}/c^2$
- Color flow: $0.3\ \mathrm{GeV}/c^2$
- **Total:** $0.6\ \mathrm{GeV}/c^2$

Our current proposal

Proposed systematic shifts:

* $B(b \to l) = 23.9\% \pm 0.7\%$.

  Includes $b \to \tau$.

* $B(c \to l) = 18.8\% \pm 2.0\%$.

  Use for all charm, incl sequential decay

Vary these independently. Here correlated != conservative.

But do we also need to separate charm further?

B-JES systematics

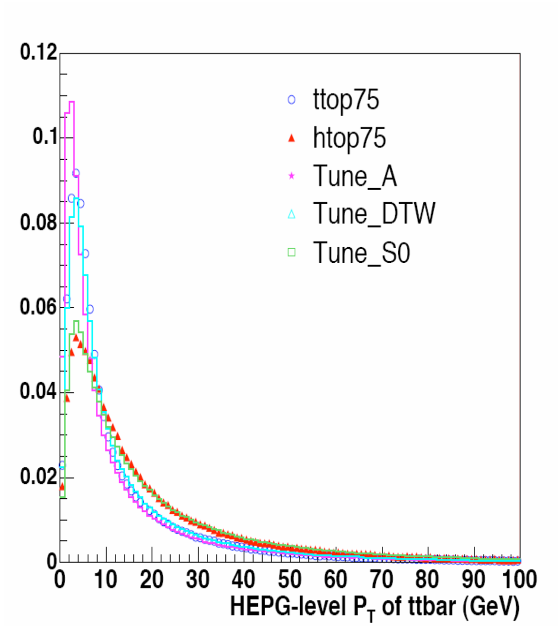
- What fraction of momentum of b quarks is carried by the b hadron (z)?
- Describe using phenomenological models. Best model (?) seems to be the Bowler parameterization

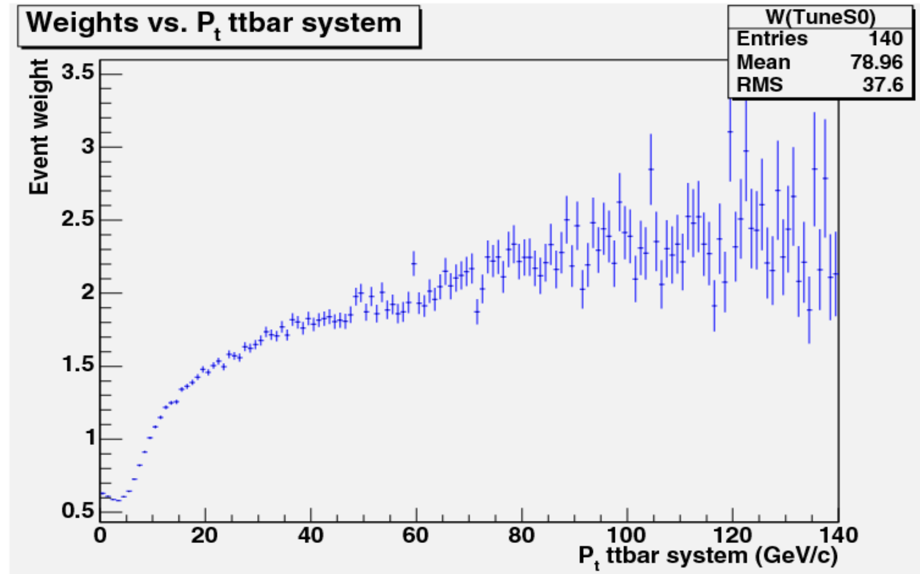
$$f(z) \propto z^{-(1+br_q m_q^2)}(1-z)^a \exp[\frac{-b(m_{had}^2 + p_T^2)}{z}]$$

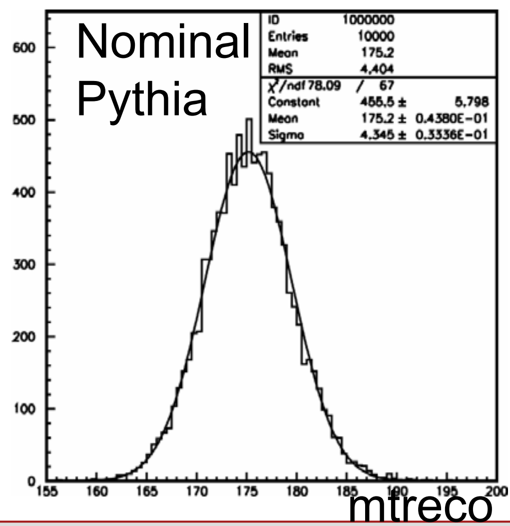
  - a, b, r_q: free parameters
  - m_q: mass of b quark (4.8 GeV)
  - m_{had}: mass of b hadron
  - p_T: transverse momentum of hadron, z direction given by flight direction of quark

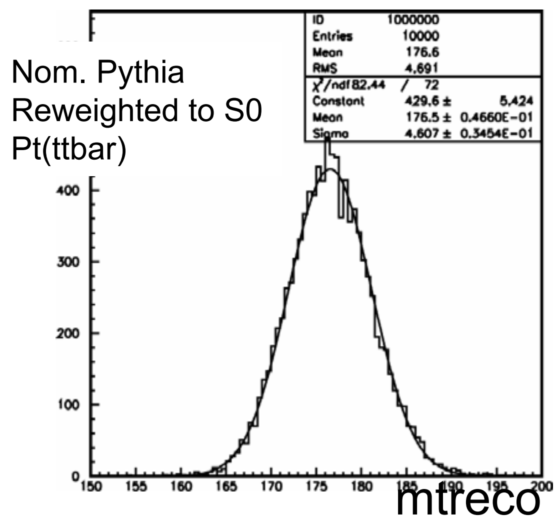
General idea:
1. Vary a, b, r, calculate W(z) for each event
2. Use W(z) to reweight pseudodata

CR



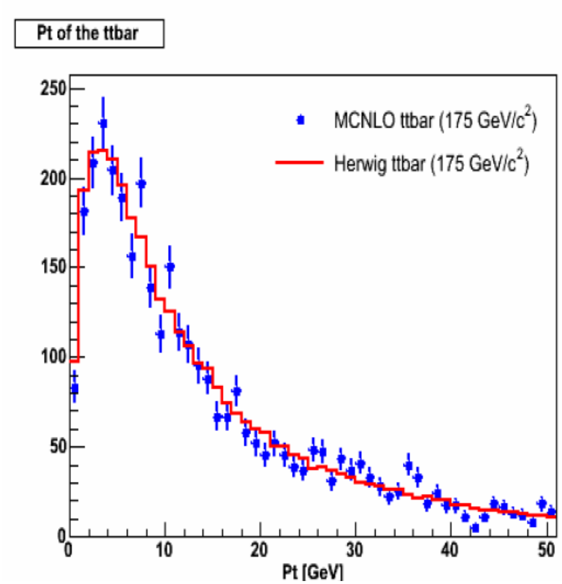




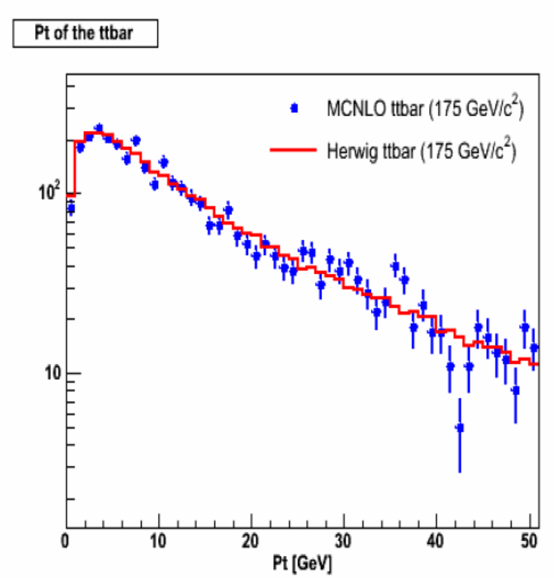


ΔMt=1.3+/-0.06 GeV

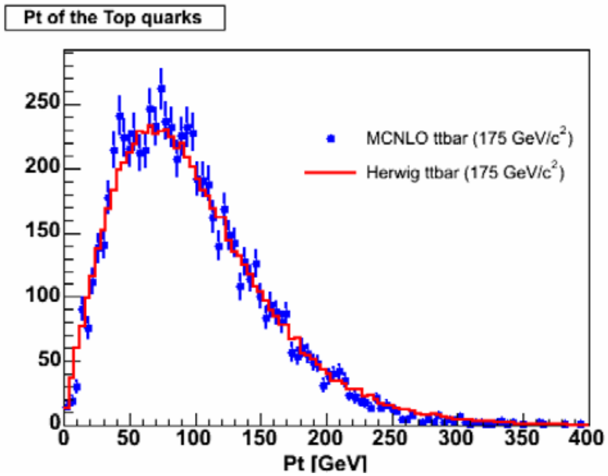
MC@NLO



Pt of the ttbar
MCNLO ttbar (175 GeV/c^2)
Herwig ttbar (175 GeV/c^2)
Pt [GeV]



Pt of the ttbar
MCNLO ttbar (175 GeV/c^2)
Herwig ttbar (175 GeV/c^2)
Pt [GeV]



Pt of the Top quarks
MCNLO ttbar (175 GeV/c^2)
Herwig ttbar (175 GeV/c^2)
Pt [GeV]